Flame/Flow-Field Dynamics for Low Swirl Burners

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Work done by students

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Introduction

- Objective
  - *Examine the acoustics/combustion interaction for lean premixed low swirl stabilized flames*
  - The lean premixed burner used here has reduced emissions and good flame stability
  - This burner is starting to see broader industrial use, which makes higher pressure behavior especially interesting

- Combustion Instability
  - Presence of an unwanted large amplitude pressure oscillation inside the combustion chamber
    - Vibration, noise, increased emission…
  - Driving factors:
    - Thermoacoustic coupling, hydrodynamics, mixture-fraction oscillations…

Introduction - Thermoacoustic Coupling

- Wave equation

$$\nabla^2 p' - \frac{1}{a^2}\frac{\partial^2 p'}{\partial t^2} = -\frac{1}{a^2}\frac{R}{C_v}\frac{\partial q'}{\partial t} + g$$

  - Superscript ()' denotes deviations from mean value, *a* is the speed of sound, and the term *g* contains all influences other than that of heat addition.

- Energy per cycle

$$\Delta\varepsilon_n(t) = (\gamma - 1)\frac{\omega_n^2}{E_n^2}\int dV \int_t^{t+\tau_n} \frac{p'_n}{\bar{p}}\frac{q'}{\bar{q}}\,dt$$

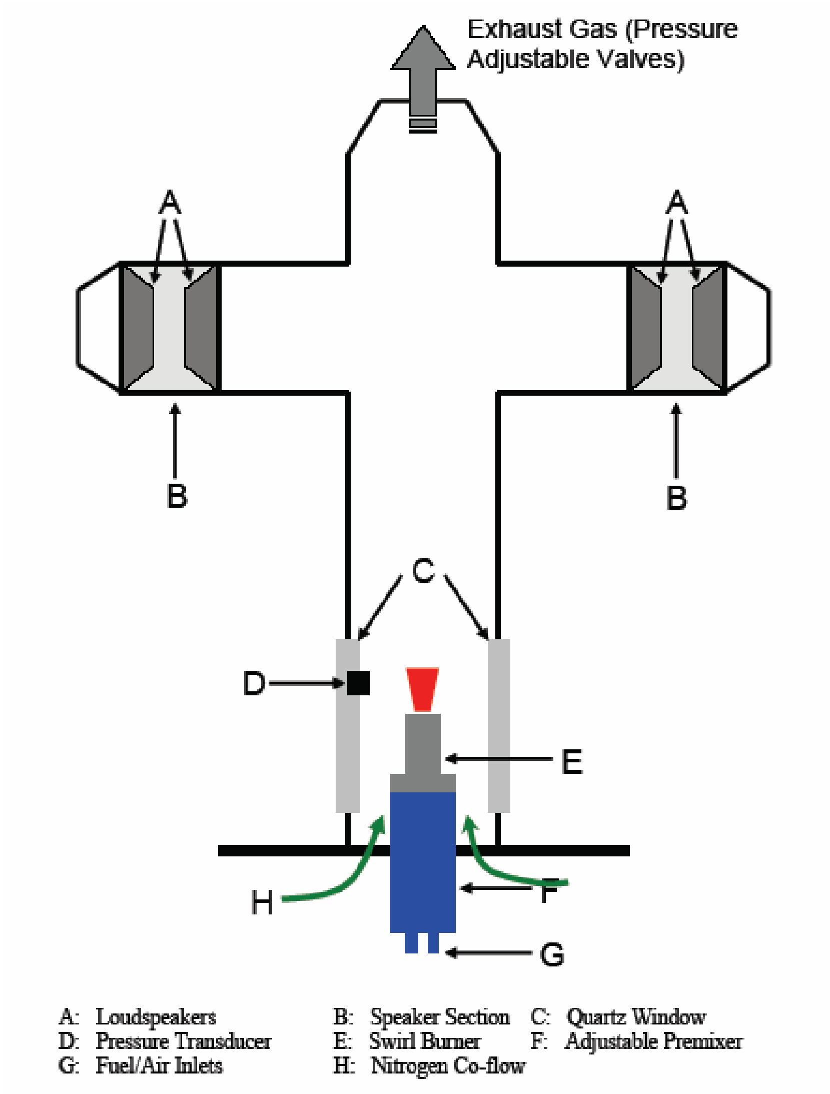
  - *n* denotes different modes of the acoustic oscillation

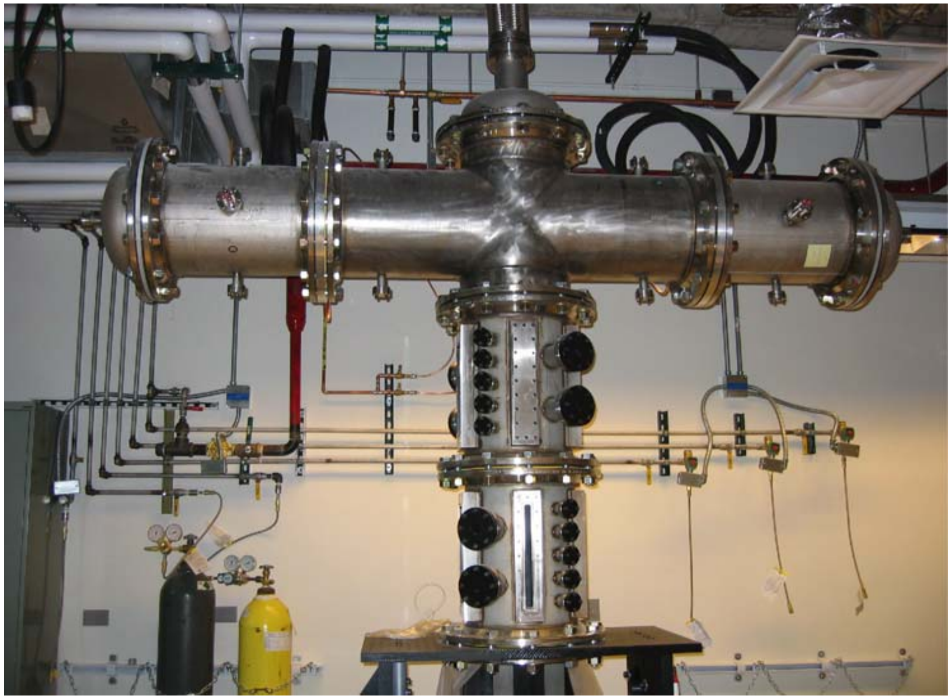
- Rayleigh Index

$$R_f = \int_0^1 \frac{p'q'}{p_{rms}\bar{q}}\,d\xi$$

  - Positive R_f means that pressure oscillation and heat release are in phase and hence the oscillation is enhanced
  - In reality, a flame could be stable while exhibiting a positive Rayleigh Index since dissipation is not included in this equation

Experimental System

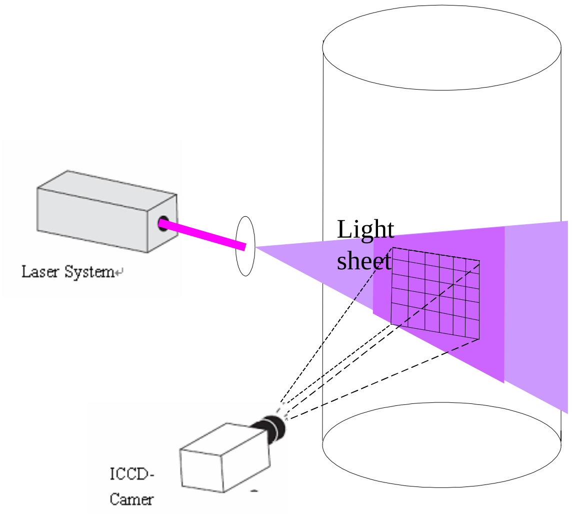




- Chamber size:
  - Diameter 12”, height: 6’
- Low swirl burner:
  - Diameter 1”, Length 2”

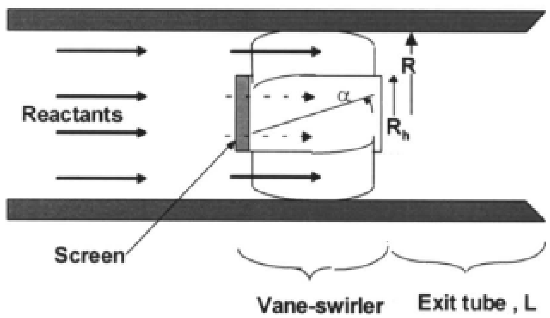
Experimental System - Imaging

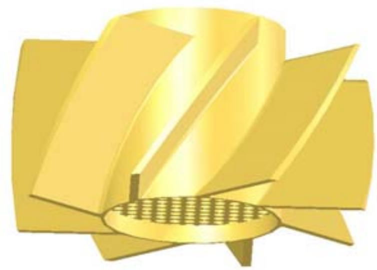
- Laser system
  - Nd:YAG pump laser, dye laser, frequency doubler
  - Sheet-forming optics
- Camera system
  - ICCD camera
  - View field: 8.9cm*8.9cm(512*512)
- Excitation – detection
  - 283 nm pump beam with 310-350 nm detection



Simplified schematic view of imaging system

Experimental System – Burner Configuration





- Robert-Cheng-design low-swirl burner
- Operational principle
  - generate the necessary flow divergence for stabilization (local flow velocity equals the flame speed)

Experimental Conditions

- Reactants

  fuel: methane; oxidizer: air

  equivalence ratio: $\Phi=0.5$

- Flow rates:

  air: 100 slpm, methane: 5 slpm

  reactants: 3.48m/s (outlet of the burner)

- Enforced acoustics

  frequency: 22-120Hz

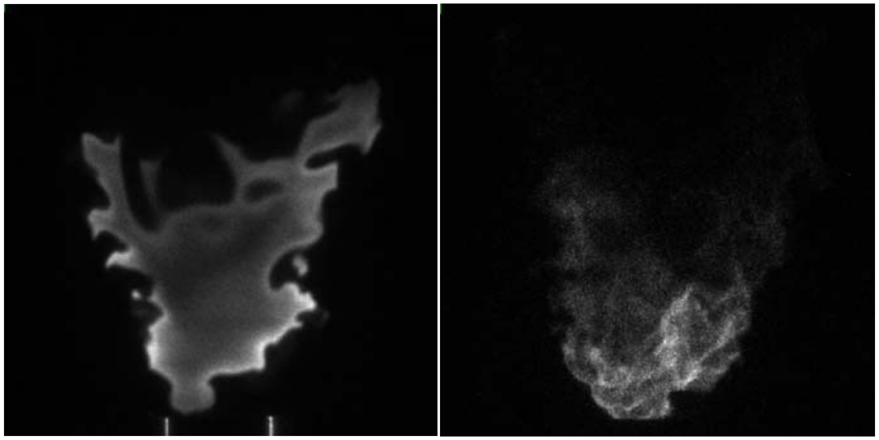
  amplitude: ~0.05%

- Chamber bulk pressure:

  P= 1atm

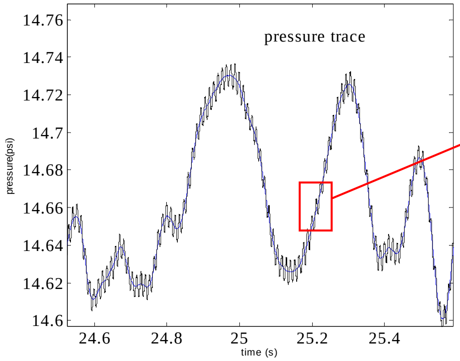
Raw Data

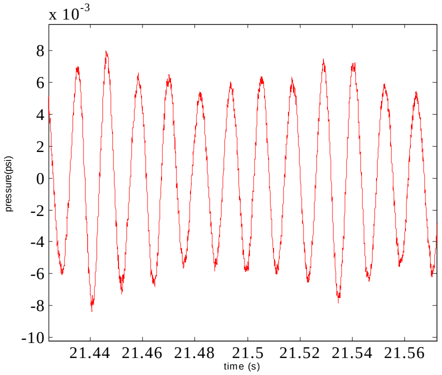
- Images



OH-PLIF(gate 100ns) OH* (gate 400us)

- Pressure signal





Bulk pressure fluctuation Acoustically enforced fluctuation

Data Reduction

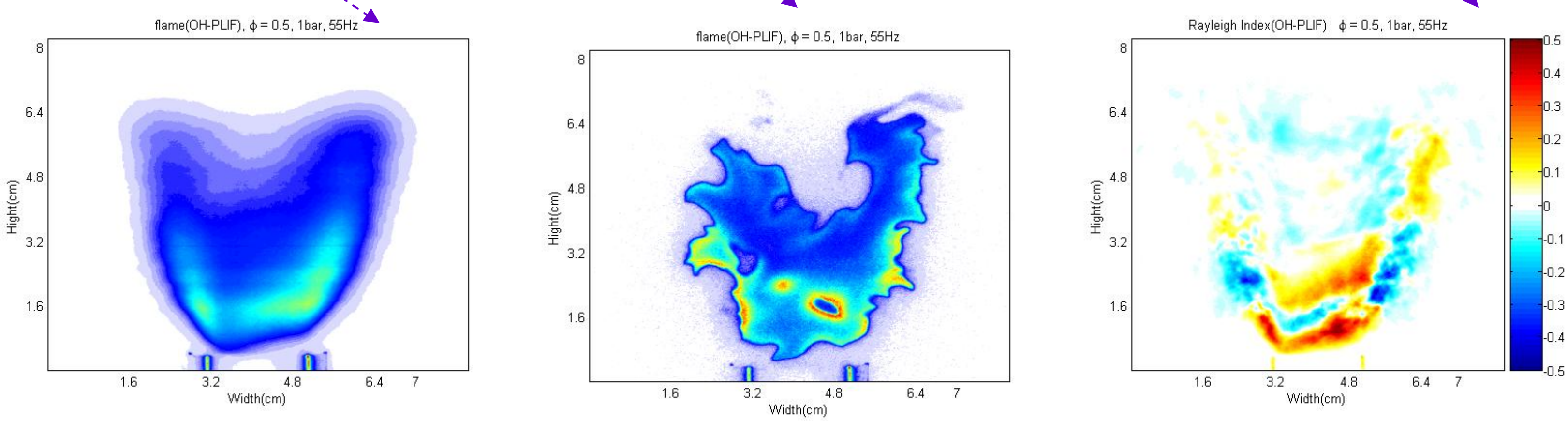
Instant Image [OH]

Averaged Image $\overline{[OH]}$

Instant p'

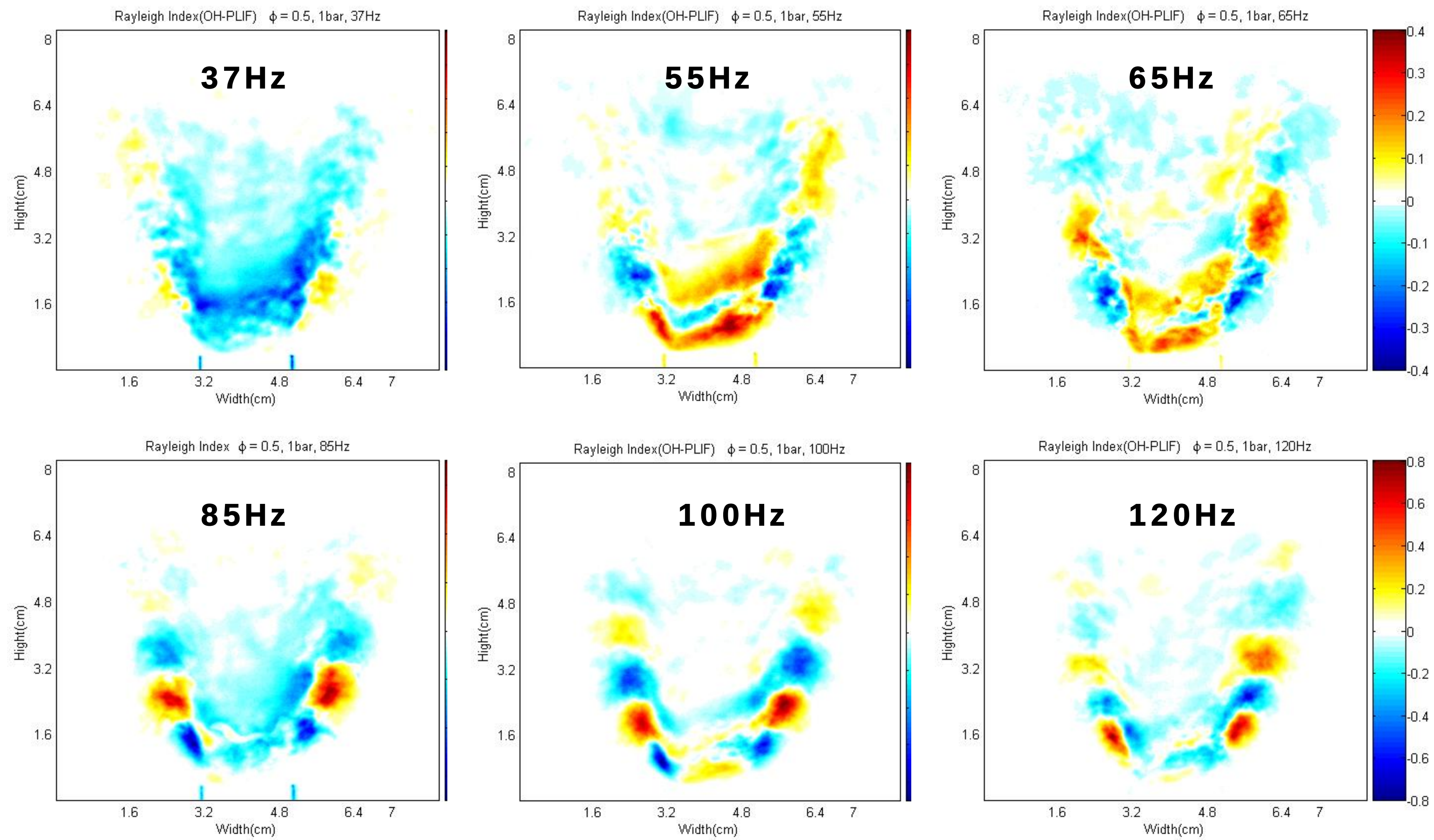
Instant Image [OH]'

Rayleigh Index



- No clear structure seen from OH concentration
- Pattern appears in Rayleigh Index

Rayleigh Index distribution from OH-PLIF



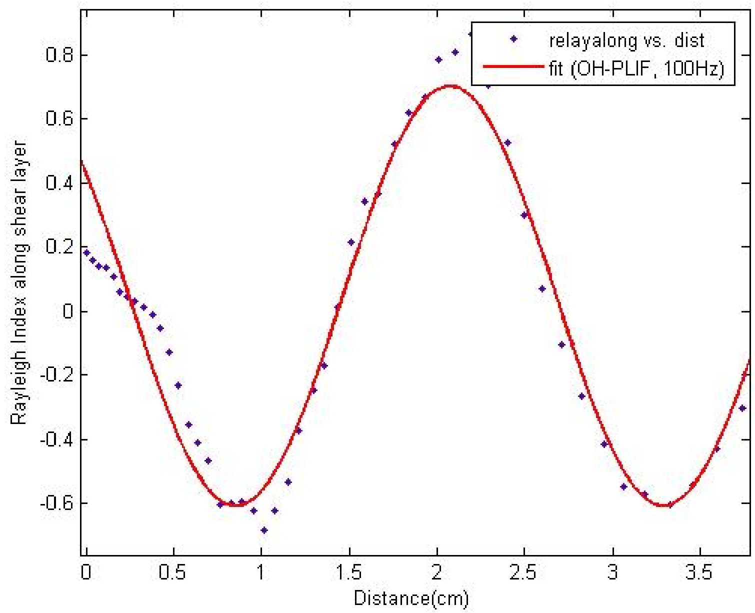
Rayleigh Index at the center plane of the flame
(f=37, 55, 65, 85, 100, 120 Hz)

Results

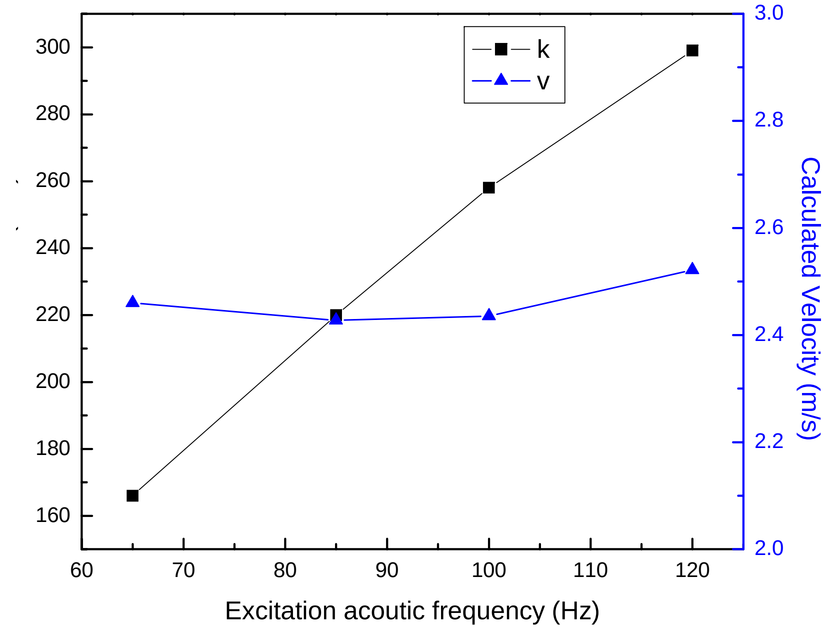
- The pattern becomes more established at higher frequency
- The size of the structure decreases as frequency increases
  - As expected for a frequency linked flow phenomena
- ‘Lock on’ observed
  - The frequency of vortex rollup can lock onto the frequency of a sound field if the amplitude of the acoustic oscillation is large enough and its frequency is sufficiently close to the natural frequency of vortex shedding.

Results

- The Rayleigh Index through a line running between the vortex core is extracted and a curve fit is applied



Rayleigh Index along the structure, 100Hz

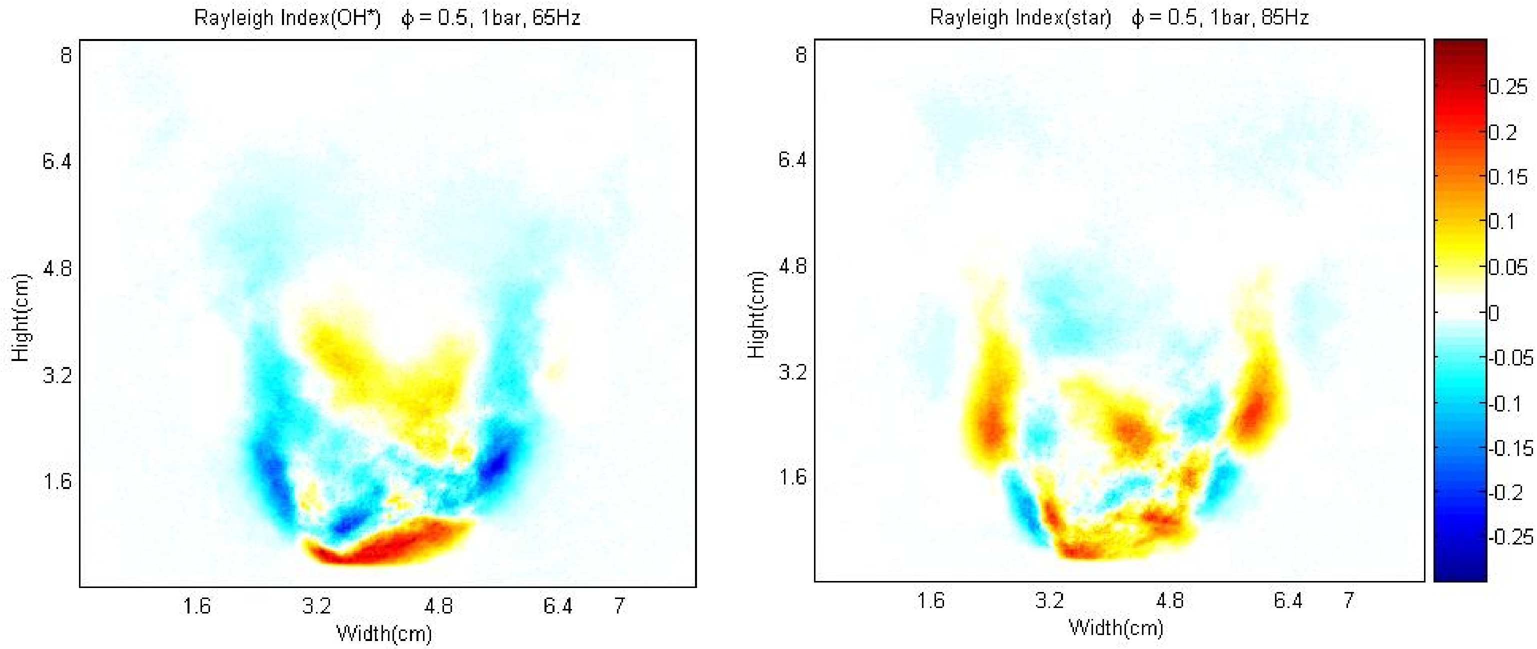


Wavenumber and calculated velocity

$$\boldsymbol{k} = {2\pi}/{\lambda} = 258$$ ---Wave number

$$v = {2\pi f}/{k} = 2.43 m/s$$ ---comparable with the fluid velocity

Comparison of OH-PLIF & OH*



Rayleigh Index distribution from OH*

- Chemiluminescence is not as helpful as PLIF to study the structures of interest for this flame.

  * denotes chemiluminescence

On-going and Future Work

- Vary the imposed acoustic wave
  - Vary the amplitude
  - Broaden the frequency range
- Phase resolved information
  - The method laid out can be useful for examining flow structures that occur at any frequency and for any reason – how do we make the best use of this?
- High pressure
  - Currently assessing data at 3 atm
  - Plans are to gather data up to a bulk pressure of 5 atm

Conclusions

- Investigated the coupling of combustion and enforced acoustics for a low swirl stabilized lean premixed flame

- Toroidal structures are observed from Rayleigh Index distribution

- A nearly constant convection velocity of the structure is observed for different frequencies
  - Implying lock-on that dictates vortex size but that des not affect the advection speed

- Chemiluminescence is not as helpful as PLIF to resolve the structures of interest for this flame